

Creation of Strange Matter at Low Initial μ/T

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We demonstrate that the creation of strange matter is conceivable in the midrapidity region of heavy ion collisions at Brookhaven RHIC and CERN LHC. A finite net-baryon density, abundant (anti)strangeness production, as well as strong net-baryon and net-strangeness fluctuations, provide suitable initial conditions for the formation of strangelets or metastable exotic multistrange (baryonic) objects. Even at very high initial entropy per baryon $S/A^{\text{init}} \approx 500$ and low initial baryon numbers of $A_B^{\text{init}} \approx 30$ a quark-gluon-plasma droplet can immediately charge up with strangeness and accumulate net-baryon number.

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Strangelets can be thought of as multistrange quark clusters. They may exist as (meta)stable exotic isomers of nuclear matter [1]. It was speculated that strange matter might exist also as metastable exotic multistrange (baryonic) objects (MEMO's) [2].

The possible creation—in heavy ion collisions—of long-lived remnants of the quark-gluon plasma (QGP), cooled and charged up with strangeness by the emission of pions and kaons, was proposed in [3–5]. Strangelets can serve as signatures for the creation of a quark gluon plasma. The detection of strangelets would verify exciting theoretical ideas with consequences for our knowledge of the evolution of the early Universe [6], the dynamics of supernova explosions, and the underlying theory of strong interactions [7]. Currently, at both the BNL Alternating Gradient Synchrotron and at the CERN Super Proton Synchrotron (SPS) experiments are carried out to search for MEMO's and strangelets, e.g., by the E864, E878, and NA52 Collaborations [8].

Here we want to point out that such exotic states of matter, as well as multistrange hadronic objects, can be created in heavy ion collisions even at collider energies, where such a process has received no attention so far, because the common belief was that the (strange) baryon densities vanish at midrapidity, at both the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC). We argue, however, that this conclusion was premature. This is due to the following effects which have an impact on the “initial” conditions of the further evolution:

(i) Fluctuations of the stopping power can provide finite baryochemical potential μ_B at midrapidity in a small fraction of all events.

(ii) Fluctuations of the net-baryon and -strangeness content between different rapidity bins within *one* event can be large (Fig. 1).

(iii) Strange (anti)baryon enhancement can occur due to collective effects (e.g., a chiral phase transition) (Fig. 2).

The present simulations using FRITIOF 7.02 [9] in fact show that even in very central collisions of lead on lead at $\sqrt{s_{\text{c.m.}}} = 6.5$ TeV per nucleon the midrapidity region could contain net baryons, i.e., a nonvanishing, positive quark chemical potential μ_q [10]. This is shown in Fig. 1, where the event-averaged rapidity densities of net baryons, hyperons, and antihyperons are depicted. Note that the strange to nonstrange hadron ratios predicted by this model are the same for pp and AA collisions at 200A GeV/c (CERN SPS) and that the strange particle numbers for AA underpredict the data [11]. This deficient

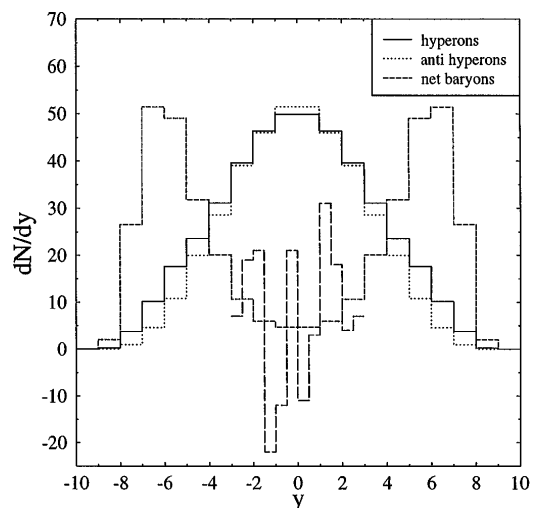


FIG. 1. Event-averaged rapidity density of net baryons, hyperons, and antihyperons in collisions of Pb + Pb at 6.5 TeV and $b = 0$, calculated with FRITIOF 7.02. For the midrapidity range, the net-baryon distribution of one single event is also depicted.

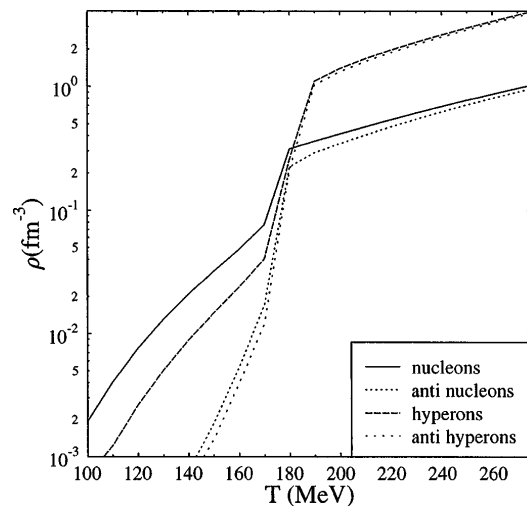


FIG. 2. Densities of (anti)nucleons and (anti)hyperons as functions of temperature for fixed $\mu_q = 100$ MeV and strangeness fraction $f_s = 0$, calculated with a relativistic meson-baryon field theory which implements hyperon-hyperon interactions.

treatment of the collective effects in the model leads us to take the numbers only as lower limits of the true strange particle yields at collider energies. The rapidity density in a unit interval around $y_{c.m.}$ deviates from the average value (5–10) by more than ± 20 with a 15% probability. The dN/dy of a randomly selected single event is drawn for illustration in the midrapidity region.

Relativistic meson-field models, which, at high temperature $T_C \approx 180$ MeV, qualitatively simulate the chiral behavior of the nuclear matter, exhibit a transition into a phase of massless baryons [12]. Every (anti)-baryon species (hyperons included [2]) shows approximately the number density of normal nuclear matter ($\rho_0 \approx 0.16 \text{ fm}^{-3}$) near T_C even if $\mu \approx 0$. Thus, the fraction of (anti)strange hyperons increases by 1–2 orders of magnitude at T_C . Several hundred (anti)baryons, the majority being (anti)hyperons, may then fill the hot midrapidity region. Figure 2 shows this transition for (anti)nucleons and (anti)hyperons at small μ . Above T_C all effective masses are small and the relative yields in the medium are dictated by the isospin degeneracy, thus favoring (anti)hyperonic matter. This scenario would allow for the creation of metastable exotic multistrange objects (MEMO's) [2]. However, the high temperature will suppress the formation of clusters of mass A by $e^{-A(m-\mu_B)/T}$.

Domains of nonvanishing net baryon (antibaryon) density with finite s (\bar{s}) content will occur stochastically. Thus, the finite chemical potential is locally caused by the fluctuations of newly produced particles, not by the stopped matter. If such a phenomenon persists also for the deconfined phase, baryon concentration and strangeness separation can result in the production of strangelets and antistrangelets with roughly equal probability.

Fluctuations of the net baryon and net strangeness number can be expected at midrapidity (or fluctuations along

different rapidity intervals). The average number of initial quarks and antiquarks (before hadronization) in a rapidity interval is approximately $1/2 dN_\pi/dy \Delta y$, for half of the pions are made by the quarks and the other half by the gluons. For RHIC energies dN_π/dy has been estimated to be between 1100 and 1600 and for LHC energies to reach up to 4000 in central Pb + Pb collisions [13]. Hence the quark number is roughly 500 for RHIC and up to 2000 for LHC in a rapidity interval $\Delta y \sim 1$. [In an equilibrated plasma the total number of quarks is $N \sim \rho_q \pi R^2 \Delta z$ within $\Delta z = 1\text{--}2$ fm in the early stage of the hydrodynamical expansion. According to $\rho_q = g(3/4\pi^2)T^3 \zeta(3) \approx 1.1T^3$ for a degeneracy of $g = 12$ these numbers correspond to temperatures of $T \sim 250\text{--}500$ MeV.] Let us assume a quark number of $N = 500$. A similar consideration holds for strange and antistrange quarks, and let us take here $N_s = 200$. We now assume independent fluctuations according to Poissonians within this rapidity interval. In fact the actual width of the fluctuation at collider energies could be much broader due to Koba-Nielsen-Olesen (KNO) scaling of particle multiplicity distributions in elementary pp collisions. KNO scaling implies that at sufficiently high energies the multiplicity distribution is an energy-independent function of $n/\langle n \rangle$, where $\langle n \rangle$ is the mean value. The validity of KNO scaling at collider energies up to $\sqrt{s} = 62$ GeV and the observation of even broader distributions at $\sqrt{s} = 546$ GeV is discussed in [14]. To justify the assumption of independent fluctuations of B and \bar{B} despite the local compensation of quantum numbers, one has to estimate the typical relative momenta within a quark-antiquark pair. If one follows the parton cascade concept embodying perturbative QCD [15], the average $\sqrt{\hat{s}}$ of first parton-parton interactions ($gg \rightarrow q\bar{q}$ being the most important contribution) should be of the order of 5–10 GeV at LHC energies. The produced B and \bar{B} , carrying about 0.4 of the (anti)quark momenta, would thus be separated in rapidity by at least one unit (with a typical transverse momentum of about 500 MeV each).

We regard subsystems of one unit of rapidity which hadronize independently. Constituent quarks and antiquarks with higher relative velocities than local thermal motion are not assumed to be in chemical contact, i.e., inhomogeneities in baryon number cannot be balanced on larger scales. This constraint is well known from hadronization models, e.g., [16]. The net baryon number in a box as described above will be $|B| > 30$ with a probability of 0.5%. Then, about 0.1% of the events will reach $|B| > 30$ with a strangeness fraction $|f_s| > 0.7$. Hence, fluctuations are certainly not negligible. If each pion carries about 3.6 units of entropy (which is true for massless bosons), the entropy per baryon content in the fireball is

$$\frac{S}{A_B} \approx 3.6 \frac{dN_\pi/dy}{dN_B/dy}, \quad (1)$$

and thus for $dN_B/dy = 30$ the S/A values range from 60 to 250. If the plasma is equilibrated, the ratio of the quark chemical potential and the temperature $|\mu|/T$ is directly related to the entropy per baryon number via

$$\left(\frac{S}{A_B}\right)^{\text{QGP}} \approx \frac{37}{15} \pi^2 \left(\frac{|\mu|}{T}\right)^{-1}. \quad (2)$$

Accordingly the ratio then varies between 0.1 and 0.4.

In the following we adopt the model of Ref. [5] for the dynamical creation of strangelets out of QGP, and apply it to the hitherto unexplored collider regime, assuming $\mu/T \lesssim 0.1$; i.e., we focus on *low initial baryon densities* and *high specific entropies*, to match the expected conditions of heavy ion collisions at RHIC and LHC, where the search for strangeness enters in the objective of the ALICE experiment [17]. Consider a first order phase transition of the QGP, represented by a bag-model equation of state, to a relativistic strange and nonstrange hadron gas. (Note that the order of the phase transition is not an established fact. For a detailed discussion of the phase structure of hadronic matter with finite strangeness content we refer to [4,18].) Strange and anti-strange quarks do not hadronize at the same time for a baryon-rich system [4]. The separation (“distillery”) mechanism [4,19] can be viewed as being due to the associated production of kaons (containing \bar{s} quarks) in the hadron phase, because of the surplus of massless quarks compared to their antiquarks. The ratio f_s of the net strangeness over the net baryon number quantifies the excess of net strangeness. Both the hadronic and the quark matter phases enter the strange sector $f_s \neq 0$ of the phase diagram almost immediately, which has up to now been neglected in almost all calculations of the time evolution of the system. Earlier studies [4,5,18] addressed the case of a baryon-rich QGP with rather moderate entropy per baryon.

The expansion of the QGP droplet is described in a hybridlike model, which takes into account equilibrium as well as nonequilibrium features of the process by the following two crucial, yet oversimplifying (and to some extent controversial) assumptions. (1) The plasma sphere is permanently surrounded by a thin layer of hadron gas, with which it stays in perfect equilibrium (Gibbs conditions)

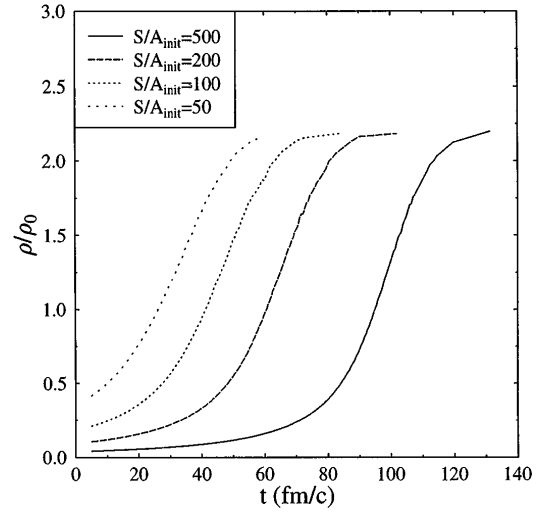


FIG. 3. Time evolution of the net-baryon density of a QGP droplet. The initial conditions are $f_s^{\text{init}} = 0$ and $A_B^{\text{init}} = 30$. The bag constant is $B^{1/4} = 160$ MeV.

during the whole evolution; in particular the strangeness degree of freedom stays in chemical equilibrium because the complete hadronic particle production is driven by the plasma phase. (2) The nonequilibrium radiation is incorporated by a time dependent freeze-out of hadrons from the outer layers of the hadron phase surrounding the QGP droplet. The global properties such as (decreasing) S/A and (increasing) f_s of the remaining two-phase system change in time according to an average rate of particles and entropy, evaporated from the hadron phase.

Figure 3 shows the large increase of baryon density of the plasma droplet (by more than 1 order of magnitude). This is a result of the dynamics of the phase transition (cf. [6,5]).

Now consider various fireballs with an initial net baryon number $A_B = 30$ and a net strangeness fraction f_s of either 0 or 0.7 as estimated above. The initial entropy per baryon ratios run between 50 and 500. Table I summarizes the initial conditions [adjusted by the (initial) chemical potentials μ_q and μ_s and temperature] and the final resulting properties of the strange quark droplet. Only

TABLE I. Various situations of a hadronizing plasma droplet of initial baryon number $A_B^{\text{init}} = 30$. The first column shows the bag constant. Then the initial conditions follow. The values for the baryon number, the strangeness fraction, and the quark chemical potential at the end (or after) hadronization are listed in the last three columns. The initial strangeness fraction is $f_s^{\text{init}} = 0$ for $\mu_s^{\text{init}} = 0$ and $f_s^{\text{init}} = 0.7$ in all other cases.

$B^{1/4}$ (MeV)	S/A^{init}	ρ_B^{init} (fm $^{-3}$)	μ_q^{init} (MeV)	μ_s^{init} (MeV)	μ/T^{init}	f_s^{final}	A_B^{final}	μ_q^{final} (MeV)
160	500	0.007	5.0	4.0	0.05	1.96	2.71	217
160	200	0.017	12.6	10.0	0.12	2.0	3.37	224
160	50	0.066	64.2	0	0.60	1.94	2.75	220
160	50	0.067	49.8	40.2	0.46	1.99	4.56	223
145	200	0.012	11.2	9.5	0.11	1.60	9.33	235
180	200	0.024	14.2	10.8	0.12	(1.83)	0	(147)

for bag constants $B^{1/4} < 180$ MeV does strange matter exist as a metastable state at zero temperature [4]. It is absolutely stable only for $B^{1/4} < 150$ MeV [6]. Even for $S/A^{\text{init}} = 200$, $f_s^{\text{init}} = 0.7$, and $B^{1/4} = 210$ MeV, does the strangeness separation work (a net strangeness content of $f_s > 1.5$ is reached), even though hadronization proceeds without any significant cooling of the quark phase, and no metastable strangelet remains left after 30 fm/c.

In any case, the thermodynamical and chemical properties during the time evolution are quite different from the initial conditions of the system. The chemical potential rises from $\mu_q^{\text{init}} \lesssim 50$ to $\mu_q^{\text{final}} \gtrsim 200$ MeV, the strange chemical potential from tens of MeV to $\mu_s^{\text{final}} > 350$ MeV (even when starting with net strangeness zero). The final baryon densities are about $\rho \approx 2\rho_0$ for all parameters covered here. High initial entropies per baryon require more time for kaon and pion evaporation in order to end up finally in the same configuration of (meta)stable strange quark matter, if this is indeed a metastable state at zero temperature.

In conclusion, we have shown that large local net-baryon and net-strangeness fluctuations as well as a small but finite amount of stopping can occur at RHIC and LHC. This can provide suitable initial conditions for the possible creation of strange matter in colliders. A phase transition (e.g., a chiral one) can further increase the strange matter formation probability. The formation of exotic multistrange objects may proceed as strangelet distillation out of a QGP droplet or as clustering of (anti)hyperons.

In a simple dynamic model the hadronization of QGP results in the formation of strangelets even for $S/A^{\text{init}} \approx 500$ and $A_B^{\text{init}} \approx 30$. The distillation of very small strangelets of $A_B \leq 10$ (see Table I) cannot be excluded for the midrapidity region at colliders. However, finite size effects of describing small strangelets neglected here might become crucial [20]. Be also reminded that the question of whether strangelets or MEMO's can exist as bound states at all is very speculative and thus still a controversial point, on which we did not focus in this Letter. Special (meta)stable candidates for experimental searches are the quark alpha [21] with $A_B = 6$ and the H dibaryon with $A_B = 2$ [22].

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